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Anisotropy of the upper critical field in the magnetic heavy-fermion superconductor URu_2Si_2

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Measurements have been performed of the upper critical field H_{c2} anisotropy in the magnetic heavy-fermion superconductor URu_2Si_2. The dH_{c2}/dT value is constant within 5% when **H** is rotated in the basal plane, whereas $|dH_{c2}/dT|$ decreases by about 35% for **H** rotated by 20°–30° out of the basal plane. Contrary to $CeCu_2Si_2$ the H_{c2} anisotropy in URu_2Si_2 is enhanced as temperature decreases below T_c. This disparity can be attributed to the different strengths of paramagnetic and spin-orbit effects responsible for the suppression of superconductivity by a magnetic field in $CeCu_2Si_2$ and URu_2Si_2.

Recently the discovery of the magnetic heavy-fermion superconductor (HFS) URu_2Si_2 has been reported.[1-3] This compound is characterized by a large linear specific-heat coefficient $\gamma = 180$ mJ/mole K^2 and exhibits both antiferromagnetic and superconducting transitions at $T_N = 17.5$ K and $T_c = 1.2$ K, respectively. The URu_2Si_2 compound, as well as the first-known HFS $CeCu_2Si_2$,[4] crystallize in the $ThCr_2Si_2$ tetragonal structure. Hence we can compare the anisotropy of superconducting properties in magnetic and nonmagnetic heavy-fermion superconductors of the same crystal structure. Furthermore, it is interesting to apply the recent results of the symmetry classification for possible superconducting classes in HFS[5] in order to identify the superconducting state in URu_2Si_2.

In this paper we present the results of the upper critical field H_{c2} measurements in a URu_2Si_2 single-crystal sample for different orientations of the magnetic field H with respect to the crystal axis.

The single-crystal samples were grown by a specially adapted Czochralski method. The as-grown crystal was annealed for 7 days at 1000 °C. A rectangular sample of typical dimensions $1 \times 1 \times 5$ mm^3 was spark cut. Thin Cu probes for dc measurements were spark welded to the sample. The electric resistivity was obtained with a standard four-probe method, using a dc current of 1 mA. During computerized measurements the signal was averaged at each temperature interval $T \pm \Delta T (\Delta T \simeq 2$ mK) over 10 data points for a given current direction. The temperature was determined with a calibrated carbon-glass thermometer. The experimental apparatus,[6] consisting of one solenoid and two pairs of Helmholz coils, makes it possible to rotate a chosen **H** vector arbitrarily in 3D space. For fixed $H = H_0$ the resistive transition was tracked and then least-square fitted between $0.2\rho_0$ and $0.8\rho_0$ by a linear dependence. The $T_c(H_0)$ value was determined as the intersection point of this dependence with the $0.5\rho_0$ straight line. Here ρ_0 stands for the residual resistivity, which for our sample was $\rho_0 = 26\ \mu\Omega$ cm. The superconducting transition at $H = 0$, $T_{c0} = T_c = 1.16$ K, has the width $\Delta T = 0.12$ K between $0.1\rho_0$ and $0.9\rho_0$.

Figure 1 shows the H_{c2}-vs-T curves for two **H** orientations, **H**‖**c** and **H**‖**a**. These data are in good agreement with $H_{c2}(T)$ results obtained in Ref. 1 on other single-crystal URu_2Si_2 samples. In low magnetic fields, $H < 0.5$ kOe, the initial slope dH_{c2}/dT is almost the same for both **H**‖**c** and **H**‖**a** directions. As the external magnetic field is increased, the $H_{c2}(T)$ curves exhibit a concave behavior in the vicinity of $T = T_c(H = 0)$.

Figure 2 displays the angular dependence of the dH_{c2}/dT derivative determined for **H** rotated in the basal plane. Here the dH_{c2}/dT value was calculated as the ratio $H(=3\ \text{kOe})/[T_{c0} - T_c\ (H = 3\text{kOe})]$. No H_{c2} anisotropy has been found in this case, at least within the experimental error bars of approximately 5%.

The dH_{c2}/dT vs θ dependencies are shown in Fig. 3 for **H** rotated by an angle θ away from the a axis into the ac

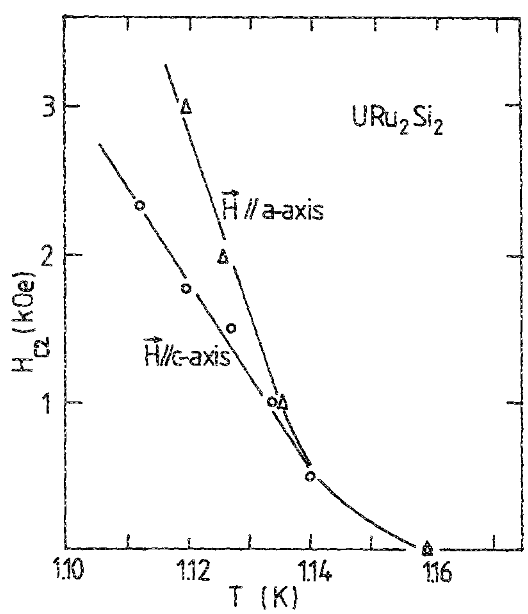

FIG. 1. Temperature dependencies of the upper critical field H_{c2} in URu_2Si_2 for **H**‖**a** (△) and **H**‖**c** (○).

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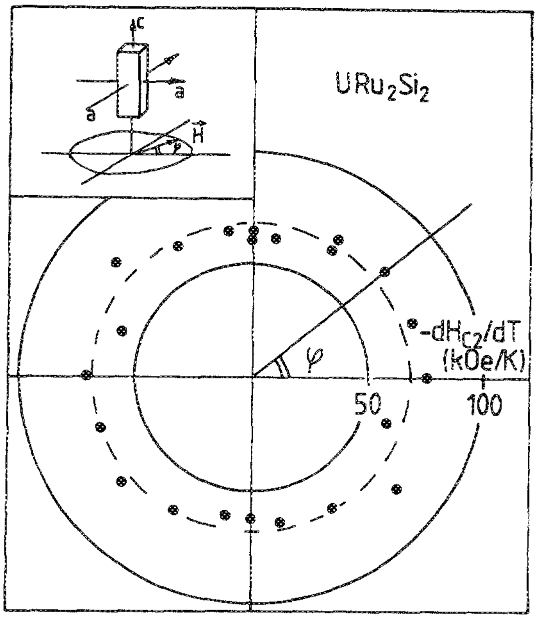

FIG. 2. Angular dependence of the derivative $-dH_{c2}/dT = H(=3$ kOe$)/T_c(H=0) - T_c(H=3$ kOe$)$ for H being rotated in the basal (ab) plane.

plane. A 35% decrease is found in the slope $|dH_{c2}/dT|$ for H rotated by 20°–30° out of the basal plane. The dH_{c2}/dT anisotropy decrease becomes even larger ($\approx 50\%$) when we determine the dH_{c2}/dT value as the ratio $[H(=3$ kOe$) - H(=1$ kOe$)]/[T_c(H=1$ kOe$) - T_c(H=3$ kOe$)]$ corresponding to the slope of linear parts of H_{c2}-vs-T curves in Fig. 1.

The main features of the H_{c2} anisotropy in URu_2Si_2, especially the H_{c2}-vs-ϕ dependence for H lying in the basal plane, are the same as in $CeCu_2Si_2$.[7] However, at the same time, there are some important differences in the $H_{c2}(T)$ behavior between URu_2Si_2 (see Figs. 1–3) and $CeCu_2Si_2$.[7] First of all, the H anisotropy in $CeCu_2Si_2$ is larger for temperatures close to T_{c0}, whereas in URu_2Si_2 the H_{c2} anisotropy increases from zero as T becomes less than T_{c0}. This is illustrated in Fig. 1. On the other hand, the dH_{c2}/dT vs θ dependence for H being rotated from the a to c axis is much sharper for $CeCu_2Si_2$ than for URu_2Si_2 (Fig. 3). The difference in the H_{c2} anisotropy of $CeCu_2Si_2$ and URu_2Si_2 can be interpreted in terms of the paramagnetic effect being more significant (see below) for the suppression of superconductivity by a magnetic field in the case of URu_2Si_2. While the spin-orbit scattering is expected to be larger in URu_2Si_2 than in $CeCu_2Si_2$, its exact influence on H_{c2} as a function of orientation is unknown. Further critical field studies at lower temperatures are warranted.

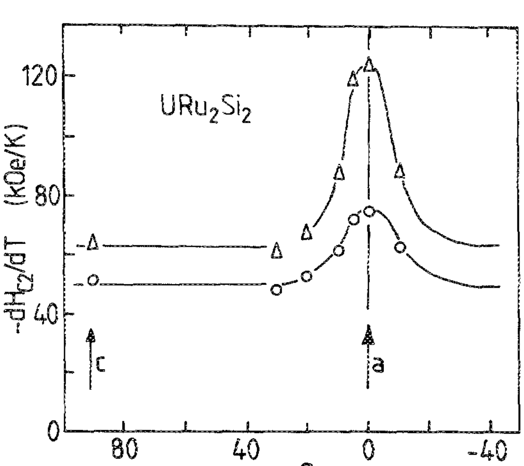

FIG. 3. Angular dependence of the derivative $-dH_{c2}/dT$ for H rotated from the a to c axis. For the lower curve $-dH_{c2}/dT = H(=3$ kOe$)/T_c(H=0) - T_c(H=3$ kOe$)$, whereas for the upper curve we use the slope of the linear parts of the H_{c2}-vs-T curves between 1 and 3 kOe (see Fig. 1).

The 2D ferromagnetic ordering[8] of the strongly Kondo screened effective moments in the basal planes of URu_2Si_2 reduces the $H_{c2}(0)$ value for $H \| c$, whereas for H lying in the basal plane, the electron orbits intersect many different planes with oppositely oriented spins (the interplane coupling is antiferromagnetic) and this leads to a higher $H_{c2}(0)$. Qualitatively this is in agreement with the observation that the H_{c2} anisotropy increases as T is further decreased.

The absence of the fourfold $H_{c2}(\phi)$ rosette in the basal plane (Fig. 2) excludes the possibility of p-wave (odd parity) pairing in URu_2Si_2, as was shown by symmetry considerations by Volovik and Gor'kov.[5] However, a slight chance for such pairing still remains if, due to the fact that the electron effective mass along the c axis is much larger than in the basal plane, the fourfold rosette in the basal plane is strongly smeared out, as was calculated by Burlachkov.[5] In this situation we probably could not observe an $H_{c2}(\phi)$ rosette within the limits of our error experimental bars (see Fig. 2). Experimentally there are no indications of an anisotropy of the electron effective mass. Still, the situation is complicated by the gapped Fermi surface due to the magnetic ordering at 17.5 K.[1,3]

In conclusion, we have measured the H_{c2} anisotropy in the magnetic HFS URu_2Si_2. The H_{c2} behavior at fixed temperature in URu_2Si_2 is similar to that in $CeCu_2Si_2$, but the temperature dependence of the ratio $H_{c2}(H\|a)/H_{c2}(H\|c)$ and the θ ($a \rightarrow c$ axis) dependence of $-dH_{c2}/dT$ are quite different for these two compounds. This indicates the importance of magnetic ordering for the suppression of superconductivity in URu_2Si_2 by a magnetic field.

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